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EFFECTS OF THE VARIABLE LORENTZ FORCE ON THE CRITICAL CURRENT IN ANISOTROPIC SUPERCONDUCTING THIN FILMS (POSTPRINT)

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14. ABSTRACT
When a current is applied perpendicular to the vortex lattice (VL), Lorentz force may cause the VL to drift and flux-flow dissipation is observed. When the current is parallel to the applied magnetic field in a Force-Free (FF) configuration, a dissipation is also observed but at higher values of applied current. It has been suggested that pinning as well as free surfaces play an important role in the stabilization of the VL in the FF configuration. In $YBa_2Cu_3O_7$ thin films, FF configurations can be obtained when H || *ab* with the current flowing parallel to the ab-planes. In this work we study the influence of thickness, growth method and pinning centers on the dissipation mechanism at Variable Lorentz Force and FF configurations. Comparisons of experiments done at Maximum and Variable Lorentz Force show that there are two pinning regimes when the field is rotated in these configurations; one consistent with only a decrease in the applied force, indicated by the overlap of the power law exponent of the current-voltage curves as the field is rotated toward the ab-planes, and another very close to the ab-planes, where the dissipation characteristics change.

15. SUBJECT TERMS
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Effects of the Variable Lorentz Force on the Critical Current in Anisotropic Superconducting Thin Films

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***Abstract*—When a current is applied perpendicular to the vortex lattice (VL), Lorentz force may cause the VL to drift and flux-flow dissipation is observed. When the current is parallel to the applied magnetic field in a Force-Free (FF) configuration, a dissipation is also observed but at higher values of applied current. It has been suggested that pinning as well as free surfaces play an important role in the stabilization of the VL in the FF configuration. In $YBa_2Cu_3O_7$ thin films, FF configurations can be obtained when $\mathbf{H}||ab$ with the current flowing parallel to the ab-planes. In this work we study the influence of thickness, growth method and pinning centers on the dissipation mechanism at Variable Lorentz Force and FF configurations. Comparisons of experiments done at Maximum and Variable Lorentz Force show that there are two pinning regimes when the field is rotated in these configurations; one consistent with only a decrease in the applied force, indicated by the overlap of the power law exponent of the current-voltage curves as the field is rotated toward the ab-planes, and another very close to the ab-planes, where the dissipation characteristics change.**

***Index Terms*—Critical current, Lorentz force, superconducting films, superconducting tapes, vortex pinning.**

I. INTRODUCTION

HIGH temperature superconductors (HTS) are aimed for use in several applications such as cables and rotating machinery. In order to reach that goal high values of critical current I_c and critical current density J_c must be attained both at self-field and in presence of an applied magnetic field ($\mathbf{H}$). Great advances have been done in both of these areas, by reducing the J_c thickness dependence [1] as well as by increasing the in-field J_c in different field and angular regimes [2]–[4]. However, most of the in-field J_c studies have been made using the maximum Lorentz force configuration (i.e. $J \perp \mathbf{H}$), but in applications this is not always the case. Therefore it is important to study other configurations where J and $\mathbf{H}$ are not perpendicular to each other, with the goal of identifying which defects or mechanisms are responsible for increasing J_c in these situations and, if possible, to increase J_c even further. If this goal could be achieved, magnets and cables could be designed to take advantage of the increased J_c [5], [6]. Besides, the use of variable and force-free in applications offers other advantages, such as the decrease in the net force on the wires and therefore smaller mechanical strength requirements [5], [6].

When a current is applied perpendicular to the vortex lattice, a large enough Lorentz force causes vortices to drift and flux-flow dissipation is observed. However, if the magnetic field ($\mathbf{H}$) is rotated in the same plane than the current in a variable Lorentz force configuration (VLF), a decrease in the Lorentz force occurs, having $F = J \times \mathbf{H} = J.Hcos(\Phi)$ and a consequent higher value of critical current, with Φ being the angle between H and the c-axis, see Fig. 1. If $\mathbf{H}$ is parallel to J ($\Phi = 90°$) in the so called Force-Free (FF) configuration, dissipation is also observed but at higher values of applied current. The Force Free configuration was extensibly studied in low temperature superconductors (LTS) [7]–[11]. In the FF configuration, it has been predicted that pinning as well as free surfaces play an important role in the stabilization of the VL [7], [8], also for LTS it has been observed that $J_c(\mathrm{FF})$ increases with decreasing wire radius [7], [9]. In YBCO thin films, FF configurations can be obtained when $\mathbf{H}||ab$ with the current flowing parallel the ab-planes. With the discovery of HTS new phenomenology became important, such as the presence of high anisotropy and different types of microstructural defects that serve as pinning centers. Studies of VLF and FF configurations have been made for HTS, but mainly as a way to explore the weak links of the grain boundaries [12]–[15], the problem that dominated the performance of coated conductors (CC)until it was solved recently [16]. Granularity reduces J_c in VLF and FF configurations since it induces local meandering of the current, resulting in portions of the sample where $J \perp \mathbf{H}$ [13], [15], [17]. Despite of the work done, little or no effort has been devoted to experimentally study the effects of different pinning centers in HTS in the VLF and FF configurations.

In this work we investigate the superconducting current density vs. electric field characteristics (J-E curves) of $YBa_2Cu_3O_7$ (YBCO) thin films in the VLF and FF configurations. As we experimentally find that all the J-E curves are well described by the power-law relation $E \propto J^N$, we fully characterize them by the two parameters J_c and N. We present a comparative study of the angular dependence of J_c and N when H is rotated in maximum Lorentz force (MLF) and in variable Lorentz force configurations (see Fig. 1). We investigate a variety of samples of different pinning microstructures and thicknesses. To isolate the effects of these two parameters from those due to weak-links,

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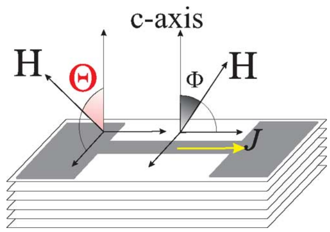

Fig. 1. Sample configuration for rotating the magnetic field ($\mathbf{H}$) in maximum and variable Lorentz force at angles Θ and Φ, measured from the c-axis.

TABLE I
PARAMETERS OF THE YBCO FILMS MEASURED. NAME, THICKNESS (t), GROWTH METHOD, CRITICAL CURRENT DENSITY AT *SELF FIELD* AND $T = 75.5$ K, (J_c^{sf}), AND $\zeta = J_c(\Theta = 90°)/J_c(\Phi = 90°)$ AT $\mu_0 H = 7$ T

Name	t [μm]	g. method	J_c^{sf} [MAcm^{-2}]	ζ @7T
YBCO/STO	2.9	HLPE	1.5	0.42
YBCO/STO	0.34	PLD	4.85	0.24
YBCO+211/LAO	0.30	PLD	4.5	0.19
YEuBCO/STO	0.12	PLD	5.95	0.47

we work only with films deposited on single crystal substrates by methods that are proved to produce compact weak-link free samples.

II. SAMPLE PREPARATION & EXPERIMENTAL SET-UP

We studied the following types of films grown by Pulsed Laser Deposition (PLD): YBCO on $SrTiO_3$(STO) [16], [18] and $LaAlO_3$(LAO) single crystal substrates, YBCO+211 grown by multiple deposition of YBCO and Y_2BaCuO_5(211) (with the 211 layers equally spaced), on LAO [3], and $Y_{2/3}Eu_{1/3}$BCO made from a mixture target on STO. We also studied YBCO films grown by Hybrid Liquid Phase Epitaxy (HLPE) [19] on STO. The thickness (t) of the YBCO films ranged from 0.12 to 3 μm. For space reasons we will show data only for four samples. All the samples measured have J_c at self-field (J_c^{sf}) consistent with state-of-the-art films for their thickness (see Table I) [16]. Bridges of width $w \sim 250-500$ μm were patterned by photo lithography.

Four-probe transport measurements with the films immersed in liquid N_2 (T $=$ 75.5 K at Los Alamos) were performed to obtain J_c (using a 1 μV/cm criterion) and N (from a linear regression of ln(E) vs. ln(J) in the range of 1 to 50 μV/cm). In-field J_c measurements were done as a function of $\mathbf{H}$ strength and orientation. In the MLF configuration $\mathbf{H}$ was applied at the plane perpendicular to the current direction ($J \perp \mathbf{H}$) with Θ being the angle between $\mathbf{H}$ and the c-axis (see Fig. 1). In the VLF configuration $\mathbf{H}$ was rotated in the same plane of the c-axis and the current (J) at an angle Φ, measured from the c-axis. The angular resolution was better than 0.1°.

Rotating in Φ and Θ allows to compare the same orientation of the magnetic field with respect to the c-axis, but with a continuously decreasing Lorentz force in the case of VLF, until the force-free (FF) configuration is reached for $\Phi = 90°$. It is always observed that $J_c(\Theta)$ (i.e. in the MLF configuration) is equal to or smaller than $J_c(\Phi)$ (i.e. VLF). At $\Theta = \Phi = 0$ both coincide since they are the same field-current configuration. This has been observed by several groups [13], [15], [17], [20]. As a general behavior we also expect that, if the pinning mechanism in the MLF and VLF is the same, then $N(\Theta)$ and $N(\Phi)$ should coincide.

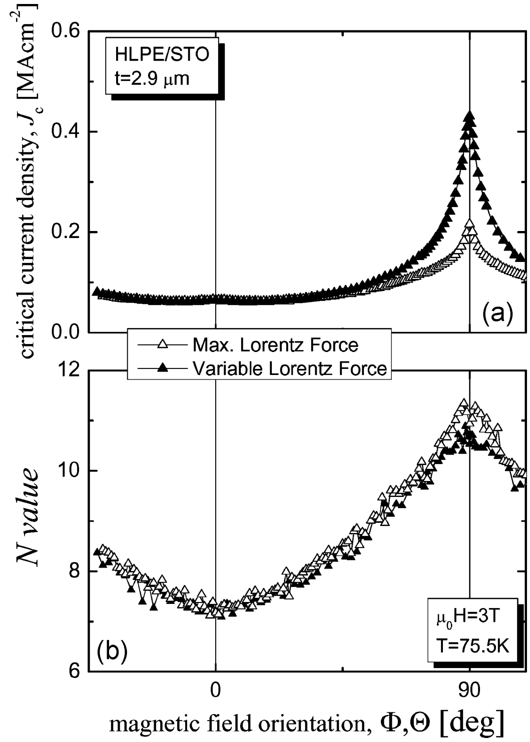

Fig. 2. (a) Critical current density J_c for a 2.90 μm HLPE sample as a function of the applied magnetic field orientation rotated in the MLF and VLF configuration (Θ and Φ respectively) at μ_0H $=$ 3T and T $=$ 75.5 K. (b) N value as a function of Θ and Φ at the same conditions.

III. RESULTS & ANALYSIS

We start with the thickest film, to minimize the effects coming from the surface of the sample [8]. In Fig. 2 we present $J_c(\Theta, \Phi)$ and $N(\Theta, \Phi)$ for a 2.9 μm thick HLPE film [19]. J_c is mostly coming from random defects, and only a small c-axis peak is observed, consistent with the small amount of threading dislocation found in this samples [19]. For MLF a small decrease in N is found near to the ab-plane's direction ($\Theta = 90°$), indicative of intrinsic pinning and low amount of extended defects at the ab-planes. This minimum is more evident at higher fields and lower temperatures [21]. For VLF, $N(\Phi) = N(\Theta)$ for most of the angular regime, except close to the ab-planes. In the VLF case the minimum in N disappears, indicating a different type of dissipation mechanism than sliding half loops [21]. The behavior found for this HLPE film is very similar to what was observed in YBCO films of similar thickness deposited by PLD on STO, with the characteristic minimum in N at the ab-planes disappearing in the VLF configuration.

We continue by describing the angular dependence for a 0.34 μm thick YBCO/STO film grown by PLD. In Fig. 3 $J_c(\Theta, \Phi)$ and $N(\Theta, \Phi)$ are plotted in the same conditions than in Fig. 2. The increase of $J_c(\Phi)$ with respect to $J_c(\Theta)$ is greater than in the HLPE sample shown above. Also, instead of a minimum in $N(\Theta)$ close to the ab-planes, a small increase is found near $\Theta = 90°$, indicative of the presence of extended defects at the ab-planes [21]. For VLF, $N(\Phi) = N(\Theta)$ for most of the angular

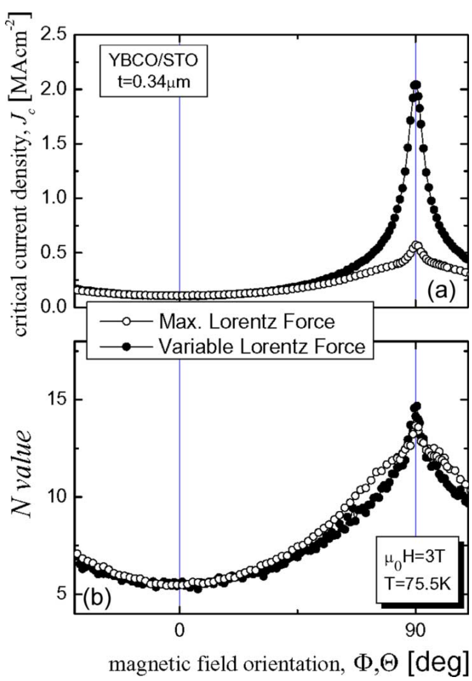

Fig. 3. (a) Critical current density J_c of a 0.34 $\mu\mathrm{m}$ PLD YBCO/STO film with H rotated in the MLF and VLF configurations at $\mu_0 H = 3\mathrm{T}$ and $\mathrm{T} = 75.5\ \mathrm{K}$; (b) N value as a function Θ and Φ respectively.

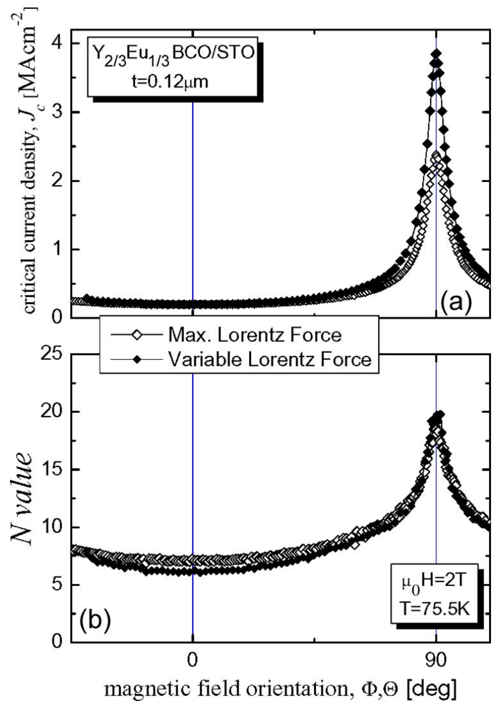

Fig. 4. (a) Critical current density J_c of a 0.12 $\mu\mathrm{m}$ PLD $\mathrm{Y_{2/3}Eu_{1/3}BCO/STO}$ film with H rotated in the MLF and VLF configurations at $\mu_0 H = 2\mathrm{T}$ and $\mathrm{T} = 75.5\ \mathrm{K}$. (b) N value as a function Θ and Φ.

regime, except close to the ab-planes where a more pronounced maximum is found for $N(\Phi)$. These differences between the PLD and HLPE films can be caused either by the difference in thickness, or by the fact that the PLD film has higher J_c^{sf} as well as more pinning at the ab-plane coming from extended defects. In order to sort out these possibilities, we measured a thinner sample with higher J_c^{sf} but less ab-planes pinning (the YEuBCO film) as well as a sample with the {\bf same} thickness and J_c^{sf} but with even more pinning at the ab-planes than the PLD YBCO/STO film (the YBCO + 211/LAO film).

In Fig. 4 we present data for $J_c(\Theta, \Phi)$ and $N(\Theta, \Phi)$ for a 0.12 $\mu\mathrm{m}$ thick PLD $\mathrm{Y_{2/3}Eu_{1/3}BCO/STO}$ [4]. We chose the YEu mixture because it produces films that are much smoother than the plain YBCO samples, and also show even less pinning at the ab-planes due to extended defects. Anisotropic J_c analysis performed in this sample [18] confirms that for H close to ab most of the pinning comes from random defects. For MLF a smooth behavior in N is found, with no signatures of correlated defect at the ab-plane's direction $(\Theta = 90^\circ)$, another indicative of high density of random pinning from the disorder induced by the mixture. For VLF we observe $N(\Phi) = N(\Theta)$ for the entire angular regime. Also, the relative improvement of J_c is small, even smaller than in the HLPE film, as can be seen in the ratio $\zeta = J_c(\Theta = 90^\circ)/J_c(\Phi = 90^\circ)$ shown in Table I. It could argued that the disorder introduced by the mixture is reducing the enhancement of $J_c(\Phi)$, but this film has a very high J_c, so weak links or granularity can be ruled out. This result indicates that the improvements found in $J_c(\mathrm{VLF})$ are not dominated by thickness or high values of J_c^{sf} and leaves the different amount of extended defects at the ab planes in the various films studied as the most likely origin of the observed differences in $J_c(\mathrm{VLF})$.

To test our hypothesis of the influence of ab-extended pinning on $J_c(VLF)$, we measured a YBCO + 211/LAO film with very similar thickness and J_c^{sf} (see Table I) but with more pinning at the ab-planes due to the equally spaced incomplete layers of 211 [3]. In Fig. 5 we show $J_c(\Theta, \Phi)$ and $N(\Theta, \Phi)$. In this sample the enhancement in $J_c(\Phi)$ is bigger than in all the other films measured with $\zeta = 0.19$. Also, a bigger peak in both $N(\Theta)$ and $N(\Phi)$ is found centered at the ab-plane's direction, indicative of higher density of extended defects at this directions and also of a clear change on the dissipation mechanism close to the ab-planes. For most of the angular range we observe the same behavior than the rest of the samples, i.e. $N(\Phi) = N(\Theta)$. This clearly confirms that the vortex dynamics in the VLF geometry is influenced by the pinning centers present in the sample, particularly, extended defects at the ab-planes.

One important point to remark is that we are not implying that granularity does not affect J_c in VLF an FF configuration. It does, but the type of pinning centers also play an important role. Thus, before inferring conclusions from the VLF about the granularity it is necessary to study the pinning properties of the films in the MLF. [14] Particularly, ζ has to be used carefully since it is not totally given by the granularity in the film as it is also governed by pinning, as can be seen in Table I where ζ ranges from 0.20 up to 0.50. Of particular interest would be to study CC grown by metal organic deposition which present a higher density of extended defects [22].

IV. Conclusions

We have studied the influence of thickness, growth method and pinning centers on the dissipation mechanism at Variable

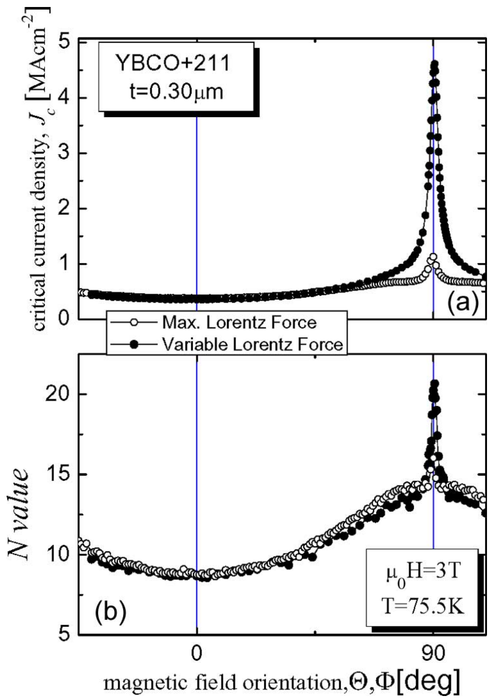

Fig. 5. (a) Critical current density J_c of a 0.30 μm PLD YBCO + 211/LAO film with H rotated in the MLF and VLF configurations at $\mu_0 H = 3$T and T $= 75.5$ K; (b) N value as a function Θ and Φ respectively.

Lorentz Force and Force Free configurations. Comparisons of experiments done at Maximum and Variable Lorentz Force show that there are two pinning regimes when the field is rotated in this configurations; one consistent with only a decrease in the applied force, indicated by the overlap of $N(\Theta)$ and $N(\Phi)$ as the field is rotated toward the ab-planes, and another very close to the ab-planes, where the dissipation characteristics change drastically, which is consistent with vortex cut and recombination [17]. We found that thickness plays a less important role than the pinning present in the films. The regime closer to the ab-planes is affected by the amount of extended correlated pinning at this direction.

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